

FUSE Observational Evidence of the Boundary Layer of MV Lyrae in the High State

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ABSTRACT

We carry out a spectral analysis of the archival *FUSE* spectrum of the VY Scl nova-like cataclysmic variable MV Lyrae obtained in the high state. We find that standard disk models fail to fit the flux in the shorter wavelengths of *FUSE* ($\lambda < 950\text{\AA}$). An improved fit is obtained by including a modeling of the boundary layer at the inner edge of the disk. The result of the modeling shows that in the high state the disk has a moderate accretion rate $\dot{M} \approx 2 \times 10^{-9} M_{\odot}/\text{yr}$, a low inclination, a boundary layer with a temperature of $\sim 100,000\text{K}$, and size $\sim 0.20 R_{wd}$, and the white dwarf is possibly heated up to a temperature $T \approx 50,000\text{K}$ or higher.

Subject headings: accretion, accretion disks - novae, cataclysmic variables - white dwarfs

1. Introduction

1.1. The VY Scl Nova-like System MV Lyrae

Cataclysmic variables (CVs) are evolved compact binaries in which the primary, a white dwarf (WD), accretes matter and angular momentum from the secondary, a star approximately on the main sequence filling its Roche-lobe. In dwarf nova (DN) and non-magnetic nova-like (NL) systems (two classes of CVs), the matter is transferred by means of an accretion disk around the WD. DN systems are found mostly in a faint, quiescent state with a low mass transfer rate ($\dot{M} \sim 10^{-12} - 10^{-11} M_{\odot}/\text{yr}$), and every few weeks to months they transit into a bright, outburst state lasting days to weeks, as the mass transfer suddenly increases by several orders of magnitude ($\dot{M} \sim 10^{-9} - 10^{-8} M_{\odot}/\text{yr}$). The transition to outburst in DNs is believed to be due to a disk instability (Shafter et al. 1986; Cannizzo 1988, 1998). NL

systems are found mainly in a high state phase, characterized by a large mass accretion rate, and from time to time the mass accretion rate suddenly drops by several orders of magnitude. The transition from high state to low state in NL is caused by a throttling of the mass transfer, possibly due to magnetic activity of the secondary star (see Warner (1995) for a review of CVs). With time, the accreted matter in CV systems forms a hydrogen-rich layer that covers the surface of the WD. When enough material is accreted (every few thousand years), the hydrogen-rich material undergoes a thermonuclear runaway and the system forms a classical nova event.

MV Lyr is a VY Scl nova-like system, spending most of its time in the high state and occasionally undergoing short-duration drops in brightness. When this happens, the magnitude of MV Lyr drops from $V \approx 12 - 13$ to $V \approx 16 - 18$ (Hoard et al. 2004). From the AAVSO online data (<http://www.aavso.org/>) it appears that MV Lyr can stay in the high state for up to ~ 5 yr, and then for a period of a few years to ~ 10 yr it spends its time alternating between high state and low state on a time scale of a few months to a year. The orbital period of the binary in MV Lyr is $P = 3.19$ hr and the mass ratio was found to be $q = M_{2nd}/M_{wd} = 0.4$ (Schneider et al. 1981; Skillman et al. 1995). Because of the small radial velocity amplitudes and the lack of eclipses, the inclination is constrained to be in the range $i = 10^\circ - 13^\circ$, though it has been remarked (Linnell et al. 2005) that the inclination could be as low as $i = 7^\circ$.

Observations of MV Lyr during a low state with the *International Ultraviolet Explorer* (*IUE*) indicated a hot WD possibly reaching 50,000K (Szkody & Downes 1982) or higher (Chiappetti et al. 1982). These observations were later confirmed when MV Lyr was observed with *FUSE* on July 7, 2002, during a low state that lasted for about 8 months. Hoard et al. (2004) carried out a spectral analysis of the *FUSE* spectrum and found that the WD must have a temperature of 47,000K, a gravity $\log g = 8.25$, a projected rotational velocity $V_{rot} \sin i = 200$ km/s, subsolar abundances $Z = 0.3 \times Z_\odot$, and a distance of 505 ± 50 pc. At the time of the observations, the magnitude of MV Lyr was possibly as low as $V \approx 18$ with a mass accretion rate no more than $\dot{M} \approx 3 \times 10^{-13} M_\odot/\text{yr}$ (Hoard et al. 2004). A follow up analysis (Linnell et al. 2005) was carried out to study the different states of MV Lyr and its secondary, based on archival *IUE* spectra, a HST/*STIS* snapshot and optical spectra. Using the parameters they derived in Hoard et al. (2004), Linnell et al. (2005) found that standard disk models did not provide adequate fits to the spectra; instead, the disk had to be modified by, for example, a truncation of the inner disk, an isothermal radial temperature profile in the outer disk, or both. These modified disk models provided some satisfactory fit to the spectra obtained in the high state, leading to a mass accretion rate of the order of $3 \times 10^{-9} M_\odot/\text{yr}$.

In the present analysis, the standard disk model fails again to provide a good fit to the observed (*FUSE*) spectrum of the system in the high state. This, however, points to a more general problem, namely that the standard disk model has failed to fit the observed spectra of many other CVs observed in the high state (Puebla et al. 2007). The direct implication is that the standard disk model itself is inadequate in the ultraviolet (UV). It is in this context that we analyze here the *FUSE* spectrum of MV Lyr in its high state. For this reason, we review next the problems encountered in the modeling of CVs in the high state.

1.2. UV Spectral Modeling of CVs in the High State

In high state systems, the UV emission predominantly originates from the disk, and for that reason these systems became of special interest, as they were expected to have an accretion disk radial temperature profile given by the analytical expression $T_{eff}(r)$ of the standard disk model. More than two decades ago, Wade (1988) used *IUE* spectra to show that CV NL systems (high state systems) systematically disagree with the standard disk model when either blackbody spectra or Kurucz stellar model spectra were used to represent the accretion disk. A much improved version was developed by Hubeny (1990) for modeling annuli of accretion disks that explicitly included calculation of synthetic spectra using the standard disk model (the codes TLDISK/TLUSTY, SYNSPEC and DISKSYN), and spectra of disks were computed (Wade & Hubeny 1998) assuming the standard disk model (Shakura & Sunyaev 1973; Lynden-Bell & Pringle 1974; Pringle 1981). UV spectra (HST, HUT, *IUE*, *FUSE*) of DNs in outburst and high brightness states of NLs were successfully modeled for a number of systems with synthetic spectra of optically thick disks (Knigge & Long 2002; Hamilton et al. 2007).

However, with time, it became clear that a significant number of systems still could not be fitted using the standard disk model (Long et al. 1994; Knigge et al. 1997; Robinson et al. 1999) as first shown by Wade (1988). Orosz & Wade (2003) suggested a disk temperature profile ($T(r)$) flatter than the standard disk model, to remediate at least partially to the problem, invoking a possible non-steady mass accretion rate and/or irradiation in the outer part of the disk. More recently, the UV spectra of RW Sex, V3885 Sgr, & UX UMa (Linnell et al. 2008, 2009, 2010) were also modeled using a modified temperature profile, and it was suggested that the outer disk temperature might increase due to its interaction with the impacting L1 stream. Maybe the most significant of all is the statistical study of Puebla et al. (2007) of 33 disk-systems which indicates that a revision of the standard model temperature profile, at least in the innermost part of the disk, is required.

These studies concentrated mainly on using UV spectra (e.g. *IUE*, HST/*STIS*, *FUSE*),

and the contribution to the UV continuum comes mainly from regions in the system where the temperature ranges roughly between $\sim 10,000\text{K}$ and $\sim 100,000\text{K}$. Lower temperatures peak in the optical, while higher temperatures peak in the extreme UV. The WD star and the disk are the main contributors to the UV flux, while the secondary star and the bright spot (the edge of the disk impacted by the incoming stream of matter) peak in the optical and near UV, respectively. For disks in CVs with mass accretion rate $\sim 10^{-8}M_{\odot}/\text{yr}$, the inner disk reaches a temperature higher than $50,000\text{K}$. These disk models, therefore, have a significant UV flux contribution from the inner region of the disk.

That same innermost part of the disk is the region where the matter in the disk has to decelerate from its Keplerian motion in order to be accreted onto the more slowly rotating stellar surface, as the centrifugal force keeps the matter from accreting. This region is known as the boundary layer (BL) and up to half the accretion luminosity can be released in this final phase of the accretion process. Therefore, the emission and heating of the BL have to be taken into account when modeling an accretion disk around a non- (or weakly-) magnetic star (Lynden-Bell & Pringle 1974; Pringle 1981). It has now become clear that the temperature profile in the inner disk is affected by the heating from the BL. Most importantly, BLs in high state have a temperature of the order of $100,000\text{K}$ - $200,000\text{K}$ (Popham & Narayan 1995; Godon et al. 1995; Piro & Bildsten 2004), which is much lower than the first analytical estimates of $\sim 500,000\text{K}$ (Pringle 1977; Pringle & Savonije 1979). Consequently, the BL of CV disk systems in the high state contributes significantly to the UV, even though it was predicted to emit only in the soft X-ray range (see also next section). Therefore, the BL has to be included in the disk modeling and the inner disk temperature profile has to be modified accordingly.

It is the purpose of the present work to include an elementary (and preliminary) model of the BL in the spectral modeling of the *FUSE* spectrum of MV Lyr taken during its high state. Since the BL has an elevated temperature, its contribution will be more pronounced in the shorter wavelengths of the spectral range of *FUSE*.

In the next section a brief review of the standard disk and BL models are given, and it is shown that the theory does indeed predict a BL contributing a non-negligible flux in the far UV. The *FUSE* spectrum of MV Lyr together with the details of the synthetic spectral modeling are presented in section 3. The results follow in section 4, and are discussed in the concluding section.

2. The Star-Disk Boundary Layer

2.1. The Standard Disk Model

The total luminosity available through accretion is given by:

$$L_{acc} = \frac{GM_*\dot{M}}{R_*}, \quad (1)$$

where G is the gravitational constant, \dot{M} is the mass accretion rate, M_* is the mass of the accreting star and R_* is its radius. This expression simply reflects the release of gravitational potential energy of the material brought onto the surface of the star ($r = R_*$) from infinity ($r \rightarrow \infty$) at a rate \dot{M} (mass/time).

In the standard disk theory (Shakura & Sunyaev 1973; Lynden-Bell & Pringle 1974), the accretion disk is axisymmetric, and geometrically thin in the vertical dimension: it has a vertical thickness H such that $H/r \ll 1$. The disk is treated with a one-dimensional radial approximation, in which the radial pressure is negligible and the matter in the disk is assumed to be rotating at Keplerian speed. The energy dissipated by viscous processes between adjacent rings of matter is instantly radiated locally in the vertical z -direction. The disk total luminosity L_{disk} is half the accretion luminosity

$$L_{disk} = \frac{L_{acc}}{2} = \frac{GM_*\dot{M}}{2R_*}, \quad (2)$$

and each face of the disk radiates $L_{disk}/2$. This is so, because the matter at the inner edge of the disk ($r \approx R_*$) retains the remaining accretion energy in the form of kinetic energy, as it rotates at Keplerian speed.

The effective surface temperature of such a disk is given by (Shakura & Sunyaev 1973; Lynden-Bell & Pringle 1974; Pringle 1981):

$$T_{eff}(r) = T_0 x^{-3/4} (1 - x^{1/2})^{1/4}, \quad (3)$$

where $x = r/R_*$,

$$\sigma T_0^4 = \frac{3GM_*\dot{M}}{8\pi R_*^3}, \quad (4)$$

and σ the Stefan-Boltzmann constant. For practical purpose the last relation is usually written

$$T_0 = 64,800K \times \left[\left(\frac{M_*}{1M_\odot} \right) \left(\frac{\dot{M}}{10^{-9}M_\odot/yr} \right) \left(\frac{R_*}{10^9cm} \right)^{-3} \right]^{1/4}. \quad (5)$$

From this it is seen that accretion disks around WD stars emit their energy in the optical and UV. The above relation is obtained by assuming a no-shear boundary condition, $\partial\Omega/\partial r = 0$, at the stellar surface $r = R_*$ (Pringle 1981). Therefore, this model does not take into account the relatively slow rotation of the WD, and it gives a disk temperature $T=0K$ (!) at the stellar surface ($r = R_*$), and a maximum temperature $T_{max} = 0.488T_0$ at $x = 1.36$. This model also neglects the spin up of the star by the disk.

This relation, however, gives a good approximation of the effective surface temperature in the disk at larger radii ($r \gg R_*$). For a typical high mass accretion rate of $\dot{M} = 1 \times 10^{-8} M_\odot/\text{yr}$, the maximum temperature in the inner disk reaches about 50,000K-100,000K, and the inner disk become the strongest emission source of the system in the UV. During the low state of NLs (or quiescent state of DNs) the mass mass accretion rate decreases down to $\dot{M} \approx 10^{-12} M_\odot/\text{yr}$, while the maximum temperature drops to less than $\approx 10,000K$, making the disk peak in the optical and barely emit any flux in the UV. The standard disk model is a good approximation for $r \gg R_*$, but in the inner disk region, one needs to model the BL between the slowly rotating stellar surface and its Keplerian accretion disk. We would like also to note here that contrary to accreting neutron stars, the irradiation of the disk by the heated WD and BL is negligible in accreting WDs (van Paradijs & McClintock 1994; Shahbaz & Kuulkers 1998; King 1998), and one does not need to take it into account when modeling accretion disks in CVs.

2.2. The Boundary Layer

Accreting WDs in CVs have stellar rotational velocities of the order of a few 100km/s (Sion 1998) or about 10% of the Keplerian velocity at one stellar radius (a few 1000km/s). Consequently, the theory (Lynden-Bell & Pringle 1974; Pringle 1981) predicts that the material at the inner edge of the disk rotating at Keplerian speed has to adjust itself to the slowly rotating stellar surface and, therefore, dissipates its remaining rotational kinetic energy. The remaining rotational kinetic energy liberated in the BL (L_{BL}) is nearly equal to half of the total gravitational energy of the accreting matter ($L_{acc}/2 = L_{disk}$), namely (Kluźniak 1987):

$$L_{BL} = L_{disk} \left(1 - \frac{\Omega_*}{\Omega_K(R_*)} \right)^2. \quad (6)$$

Because of its small radial extent and the large amount of energy dissipated there, the BL was expected to emit only in the X-ray bands. At high mass accretion rates ($\dot{M} \approx 10^{-9} - 10^{-8} M_\odot \text{yr}^{-1}$) the BL should be optically thick and its temperature was predicted to be in the range 200,000K to 500,000K (Pringle 1977; Pringle & Savonije 1979). At low

mass accretion rates, the BL should be optically thin and emit in the hard X-ray (20keV), due to either strong shocks or the formation of a X-ray emitting corona around the WD (Pringle & Savonije 1979; King & Shaviv 1984).

The first one-dimensional computations of the BL (Regev 1983; Papaloizou & Stanley 1986; Stanley & Papaloizou 1987; Regev & Hougerat 1988) were carried out by assuming the “slim disk equations” (Szuszkiewicz et al. 1988): the equations are written and solved for vertically averaged quantities but also include the transport of energy (radiation and advection) in the radial dimension. The results from these one-dimensional computations were in general agreement with the predictions and showed that the BL should be narrow with a temperature increasing rapidly inward. However, more realistic 1D simulations (Popham & Narayan 1995; Godon et al. 1995; Collins 1997; Collins et al. 1998a,b, 2000a,b) showed that the BL extends radially and vertically more than expected. The result was that at high accretion rates the BL is **not** as hot as expected, with a temperature around 125,000K (Godon et al. 1995) to 300,000K (Popham & Narayan 1995).

Numerical works in 2D (Robertson & Frank 1986; Kley & Hensler 1987; Kley 1989a,b, 1991) did not clearly reveal whether the accreting material accumulates in an equatorial belt (e.g. as claimed by Durisen (1977) and Kippenhahn & Thomas (1978)) or spreads quickly over the entire WD surface (MacDonald 1983; Livio & Truran 1987). But more recently, using the semi-analytical shallow-water approximation developed by Inogamov & Sunyaev (1999) for accreting neutron stars, Piro & Bildsten (2004) found that at high mass accretion rate ($\dot{M} > 10^{18} \text{g s}^{-1} \approx 1.6 \times 10^{-8} M_{\odot}/\text{yr}$) the combined effect of centrifugal force and pressure gives rise to two latitudinal rings of enhanced brightness above and below the WD’s equator: the “spread layer” (Inogamov & Sunyaev 1999). At lower mass accretion rate ($\dot{M} < 10^{18} \text{g s}^{-1} \approx 1.6 \times 10^{-8} M_{\odot}/\text{yr}$) the spreading is negligible and most of the dissipated energy is radiated back into the accretion disk. The effective temperature ($2 \times 10^4 \text{K} - 5 \times 10^5 \text{K}$) and rotational velocity ($1 \times 10^8 \text{cm/s} - 3 \times 10^8 \text{cm/s}$) of the spread BL are similar to those of the one-dimensional BL models (at least where they overlap in the parameter space). Some more recent simulations have been carried out to study the spread layer (Fisker & Balsara 2005; Balsara et al. 2009), however, these two-dimensional simulations do not yet include radiation hydrodynamics.

The significance of a cooler BL means that its emission in the UV band is stronger and cannot be neglected when computing the luminosity of the disk and WD. In the next subsection (sec.2.3) we summarize the BL emission one may expect to observe in the UV at different mass accretion rates based on the above mentioned investigations.

2.3. The Emission of the Boundary Layer

For $\dot{M} \approx 2 \times 10^{-8} M_{\odot}/\text{yr}$ and higher, one expects the BL to spread onto the stellar surface, with a temperature of the order of $2 \times 10^5 \text{K} - 5 \times 10^5 \text{K}$, with a velocity of the order of $0.3 - 1 \times V_K(R_*)$. The spread layer should be observable above and below the disk (Piro & Bildsten 2004). At such temperatures the BL emits mainly in the soft X-ray with some emission in the extreme UV, and possibly also far UV. The remaining part of the WD not covered by the spread layer emits in the UV and is likely to have an elevated temperature. The disk itself emits in the UV (far UV to near UV as the radius increases) and optical (outer disk). As the mass accretion rate increases, the thickness of the boundary/spread layer increases and the matter becomes advection-dominated as the heating rate surpasses the cooling rate. In this extreme case, which is achieved when the mass accretion rate approaches its Eddington limit (Godon 1997), the flow becomes spherically symmetric and the slim disk approximation for a one-dimensional BL becomes inaccurate. Instead, the vertically averaged quantities represent the spherically symmetric quantities (Narayan & Yi 1995). This implies that the results of the one-dimensional advective BL in the plane of the disk represent a massive spread layer engulfing the entire surface of the star. Such simulations have only been carried out for BL around FU Ori stars (e.g. in 1D Popham et al. (1993); Godon (1996b), and in 2D Kley & Lin (1996)) and symbiotics (Godon 1996a).

For an accretion rate in the range $3 \times 10^{-10} M_{\odot}/\text{yr} < \dot{M} < 2 \times 10^{-8} M_{\odot}/\text{yr}$, the matter does not spread far from the WD equator and most of the dissipated energy radiates back into the accretion disk. The BL remains confined to the plane of the disk, and one can expect the one-dimensional simulations to accurately represent the BL between the star and disk. In this case, the exact temperature, size and rotation rate of the BL are given in Popham & Narayan (1995) and Godon et al. (1995). The temperature is in the range $\approx 150,000 \text{K}$ (Godon et al. 1995) to a few $100,000 \text{K}$ (Popham & Narayan 1995). A modeling of the extreme UV (Chandra) spectra of some CVs (e.g. OY Car, SS Cyg & WZ Sge) in this regime of \dot{M} leads to such temperatures (Mauche & Raymond 2000; Mauche 2004). Here too, the BL emits in the soft X-ray regime with relatively more contribution to the extreme UV and far UV as the temperature decreases. The WD and the inner disk emit in the UV, the outer disk emits in the optical. The modeling we carry out in the present work is the modeling of such a BL.

For $\dot{M} < 3 \times 10^{-10} M_{\odot}/\text{yr}$, the BL is optically thin and the only UV emission is coming from the inner disk edge irradiated by the optically thin BL. That inner edge forms a ring at a radius $r \sim 1.2R_* - 1.6R_*$, rotating at Keplerian speed, with an effective temperature $T_{eff} \sim 100,000 \text{K} - 50,000 \text{K}$ (Narayan & Popham 1993; Popham 1999) for an accretion rate of $3 \times 10^{-10} M_{\odot}/\text{yr}$ and $3 \times 10^{-11} M_{\odot}/\text{yr}$, respectively. As the mass accretion rate decreases, the

ring radius increases and its effective temperature decreases. The BL emits in the hard X-ray range and the disk’s inner edge ring emits in the UV if its temperature is high enough. Such UV emission from the inner edge of the disk/BL was identified in VW Hyi (Pandel et al. 2003) and in other dwarf novae in quiescence (Pandel et al. 2005). This UV contribution from the BL has to be taken into account when modeling the UV spectra of accreting WDs in quiescence (Godon & Sion 2005). The WD emits in the UV, as does the very inner disk. The rest of the disk emits in the optical. As the mass accretion rate decreases further, the disk eventually ceases to emit in the UV.

As a consequence, the standard disk model is roughly correct for (say) $r \approx 2R_*$ and larger, at both high and low mass accretion rates. The exact value of r for which the standard disk model breaks down depends on the mass accretion rate and mass of the WD. At smaller radii the temperature in the disk-BL region increases rapidly compared to the standard model prediction.

3. Data Analysis

3.1. The *FUSE* Archival Data

MV Lyr was observed with *FUSE* on May 6, 2003 (at 20h:07m:23s UT), just after it climbed into a high state that lasted for about 4yr. The *FUSE* exposure (D9050901) consists of 7637s of good exposure time. The data were processed with the latest and final version of CalFUSE (Dixon et al. 2007) following the same procedure as in previous works (for details see Godon et al. (2009)).

The *FUSE* spectrum of MV Lyr (Figure 1) is characterized by broad and deep absorption lines from highly ionized species and the absence of Hydrogen Lyman lines (except for sharp lines from the ISM). These absorption lines are N IV ($\sim 923\text{\AA}$), S VI (933.5\AA & 944.5\AA), O VI (1131.6 & 1137.3\AA), Si IV (1062.6 & 1073\AA), Si III ($\sim 1108\text{\AA}$), P V (1118\AA), Si IV (1122.5 & 1128.3\AA), and C III (1175\AA). Such deep and broad absorption lines are often observed in CVs in high state, even in systems with a large inclination where the Keplerian velocity broadening is expected to produce a rather smooth continuum (e.g. see the *FUSE* spectrum of V3885 Sgr in Linnell et al. (2009)). These broad and deep absorption lines most likely form in a hot corona above the heated stellar surface, BL or disk. Additional transition wavelengths have been marked on the spectrum in Figure 1 and can be associated with some spectral features; however, they are not clearly detected.

There are a few sharp absorption lines from the interstellar medium such as Si II 1020\AA , C II 1036\AA , Ar I 1048.2 & 1066.7\AA , and Fe II 1145\AA . The sharp emission lines are artifacts

due to air glow or direct reflection of sunlight inside the telescope (e.g., such as the C III 977Å & He II 1168Å lines).

3.2. TLUSTY and SYNSPEC Codes

The modeling of the *FUSE* spectrum is carried out in steps. First, spherically symmetric stellar atmosphere structure as well as the vertical structure of disk rings are computed using the code TLUSTY (Hubeny 1988). For the stellar structure the input parameters are the surface gravity, effective temperature and the surface composition of the star. For the composition it is often enough to take Hydrogen and Helium and neglect the metals as long their abundance is low (say similar to solar composition), in most cases this does not affect the computed atmospheric structure. For high temperatures we use the NLTE option. For the disk rings the input is the local mass accretion rate, mass of the accreting star, radius of the star, and radius of the ring and solar composition. Alternatively, one can input for each ring the effective temperature, effective vertical gravity and the column mass at midplane.

Second, the code SYNSPEC is used to derive the detailed radiation and flux distribution of continuum and lines (Hubeny & Lanz 1995). SYNSPEC generates the output spectrum of the stellar atmosphere structure and disk vertical structure computed by TLUSTY. The input for SYNSPEC is the same as for TLUSTY and it uses the structure computed by TLUSTY as an input. Composition is specified here with an additional input file, and can include species up to iron or even zinc. In the present modeling we included only H, He, C, N, O, Si, P, and S.

In the next step the code ROTIN is used to account for rotational and instrumental broadening of the lines for the stellar synthetic spectrum, while the code DISKSYN (Wade & Hubeny 1998) is used to combine the disk rings together (where we substitute the inner rings with hot BL rings if a BL is computed) and account for rotational broadening due to Keplerian motion. Limb darkening is also included in the codes DISKSYN & ROTIN.

Boundary layer synthetic spectra are generated by computing inner disk rings with an elevated temperature matching the BL temperature obtained from theoretical estimates. The rings of the BL are then substituted to the inner disk rings. We then use a reduced χ^2_ν fitting technique to find the best fit to the observed spectrum. During the χ^2_ν fitting process of the *FUSE* spectrum taken in the high state the mass of the WD, the inclination of the system, and the composition are kept constant because they have been firmly established from previous observations. The remaining parameters, i.e. the temperature of the WD, the mass accretion rate, the number of BL rings included, and the temperature of the BL rings

are allowed to vary as they are unknown. The distance to the system is obtained *a posteriori* from the spectral fitting as an output parameter; resulting models with a distance that does not agreed with the assumed distance are rejected (see next section).

In the present work we use the following versions of the software: TLUSTY202, SYN-SPEC48, & ROTIN4 for WD photospheric spectra runing on a Linux platform (Cygwin-X) with a GNU FORTRAN 77 compiler; TLDISK195 (a previous variant of TLUSTY), SYN-SPEC43, & ROTIN3 and DISKSYN7 for disk and BL spectra runing on a Unix machine also using a GNU FORTRAN 77 compiler (the GNU FORTRAN 77 compiler runs slightly differently under Unix and Linux operating systems). The software packages and user’s guides are available online (free download) at <http://nova.astro.umd.edu/> .

4. Results

In the following spectral modeling of the *FUSE* spectrum of MV Lyr in its high state, as we derive the mass accretion rate and characterize the BL of the system, we wish to use the mass of the WD and the distance to the system as given. These parameters were derived from the *FUSE* spectrum of the system in the low state by Hoard et al. (2004), who obtained a WD surface temperature $T = 47,000\text{K}$, a gravity $\log g = 8.25$, non-solar composition $Z \approx 0.3Z_{\odot}$, and a distance $d \approx 505 \pm 50\text{pc}$. Since these parameters are extremely important, we decided to confirm the results of Hoard et al. (2004) and we carried out a modeling of the *FUSE* spectrum of MV Lyr obtained in the low state. We obtained a WD surface temperature $T = 44,000\text{K}$, a gravity $\log g = 8.1$, a projected stellar rotational velocity $V_{rot} \sin i = 200\text{km/s}$, non-solar composition $Z \approx 0.5Z_{\odot}$, and a distance $d \approx 550 \pm 50\text{pc}$. The small difference in the parameters derived is due to the facts that (i) Hoard et al. (2004) did not include rotational broadening; and (ii) Hoard et al. (2004) used the mass-radius relation of Hamada & Salpeter (1961) for zero-temperature WDs (giving $M_{wd} = 0.73M_{\odot}$ for $\log g = 8.25$), while we used the C/O-core WD model of Wood (1995) for a $\sim 45,000\text{K}$ WD. (giving $M_{wd} = 0.73M_{\odot}$ for $\log g = 8.1$ but $M_{wd} \sim 0.8M_{\odot}$ for $\log g = 8.25$), We note, however, that our results are in complete agreement with the modeling carried out by E.M.S. *within* Hoard et al. (2004)’s work. Therefore, in the following we use the following parameters: $M_{wd} = 0.8M_{\odot}$, $d \sim 500 - 550\text{pc}$, $T_{wd} = 44,000\text{K}$ and above. The abundances and stellar rotational velocity have no effects on the fitting to the *FUSE* spectrum in the high state as it is dominated by emission from the solar composition disk with a large Keplerian velocity broadening.

In the fitting of the high state spectrum, no attempt is made to model the broad and deep absorption lines. These lines form in a hot corona above the disk/BL and cannot be

modeled with the synthetic spectral code TLUSTY/SYNSPEC. The code models the lines created in the disk itself, but not in a hot corona above it. As a consequence, only the observed continuum is considered and the broad absorption lines are masked.

The WD model used initially in the combined BL + disk + WD fits to the *FUSE* spectrum of MV Lyr in the high state has $T = 44,000\text{K}$. In the high state the WD temperature could be elevated due to continuing accretion. Therefore, models with larger WD temperature are also computed (50,000K and up) but they give very similar results. This is due to the fact that the WD is not the main emitting component of the UV spectrum. The details are given below. We assume here $i = 10^\circ \pm 3^\circ$ (Schneider et al. 1981; Skillman et al. 1995; Linnell et al. 2005).

The first four models presented in Table 2 are the 44,000K WD + standard disk models with increasing mass accretion rate. All these models do not have enough flux in the shorter wavelength range to fit the *FUSE* spectrum. The model with $\dot{M} = 5 \times 10^{-9} M_\odot/\text{yr}$ gives a distance of 666pc, too large to be acceptable, and with $\dot{M} = 1 \times 10^{-8} M_\odot/\text{yr}$ the distance becomes twice the value found in the low state. As an example, a model with $\dot{M} = 3.5 \times 10^{-9} M_\odot/\text{yr}$ is shown in Figure 1, giving a distance of 557pc. The flux deficiency in the shorter wavelengths is clearly seen. The inclusion of a hotter WD does not provide a significant improvement of the model fit.

In order to increase the flux in the shorter wavelengths, the temperatures of the two inner rings of the standard disk model are modified to represent the BL. The first ring is located at $r_1 = 1.05R_*$ and the second is at $r_2 = 1.20R_*$. The temperatures of the rings (T_1 & T_2 respectively) are listed in Table 2. In the standard disk model these temperatures are below 50,000K for the accretion rate considered here. For the modeling of the BL, rings are computed with temperatures between 100,000K and 175,000K, in agreement with the BL models of Godon et al. (1995) ($\sim 125,000\text{K}$) and Popham & Narayan (1995) ($\sim 180,000\text{K}$) for the mass accretion rates considered here. In doing so, one is able to construct two models of BL: thin (first ring only) and extended (first two rings).

The standard disk model with a mass accretion rate of $3 \times 10^{-9} M_\odot/\text{yr}$ fits the long wavelength end of the *FUSE* spectrum using the assumed distance to MV Lyr. For this reason models with $\dot{M} \geq 3 \times 10^{-9} M_\odot/\text{yr}$ are not considered when including the BL, since the BL increases the flux of the model and therefore its distance becomes too large. Also, since MV Lyr is in a high state, mass accretion rates below $1 \times 10^{-9} M_\odot/\text{yr}$ are not considered (these points are discussed in the section 5).

First, an accretion disk with a mass accretion rate of $1 \times 10^{-9} M_\odot/\text{yr}$ is considered, and the BL temperature and size are then varied. It is found that the best model fits lead to a

distance of only 350pc-400pc. Since the mass accretion rate is fixed to $1 \times 10^{-9} M_{\odot}/\text{yr}$, the only way to increase the distance is to increase the contribution of the BL, by increasing its temperature and/or size. In doing so, the models that give an acceptable distance (of say at least $\sim 430\text{pc}$) have actually too much flux in the shorter wavelengths, a sign that the BL contributes too much flux. Only a few of these models are listed in Table 2. These models are not better than the standard disk models: their χ^2_{ν} is as large and/or their distance is too short. The best fit models are obtained for a thin (one ring) BL with a temperature of $\sim 150,000\text{K}$ - $175,000\text{K}$. The distance for these models is, however, far too short. The inclusion of a heated WD does not improve the models and produces only a small increase in the distance.

Next, to obtain models with a larger distance, the mass accretion rate is increased to $2 \times 10^{-9} M_{\odot}/\text{yr}$. This has the effect of decreasing the relative flux contributed by the BL. These models agree with the assumed distance and have a lower χ^2_{ν} , especially the two-ring BL models. The best one-ring model is for a BL temperature of $175,000\text{K}$. This model has a relatively low χ^2_{ν} and agrees well with the distance. For the two-ring BL models, there is little difference (in terms of χ^2_{ν}) between a temperature of $100,000\text{K}$, $125,000\text{K}$ and $150,000\text{K}$ (or any combination of those) as they produce $\chi^2_{\nu} \approx 1$ with $d \approx 500 \pm 50\text{pc}$. A $150,000\text{K}$ extended (2 rings) BL model with disk and WD is shown in Figure 2. This model fits the flux in the shorter wavelength range very well ($\lambda < 970\text{\AA}$, ignoring the broad absorptions of N IV & S VI) but produces too much flux around $980\text{-}1010\text{\AA}$. Extended BL models with a lower temperature (e.g. $100,000\text{K}$) do not fit the shorter wavelengths as well, but on the other side they better fit the $970\text{-}1010\text{\AA}$ region and, consequently, they have the same χ^2_{ν} . In a last effort to improve the modeling, the temperature of the WD is increased to see how it affects the results. As the WD temperature increases the hotter BL models deteriorate slightly while the cooler BL models improve slightly. These models are listed in the lower part of Table 2 A fit with a $50,000\text{K}$ WD, an extended $100,000\text{K}$ BL and a $2 \times 10^{-9} M_{\odot}/\text{yr}$ accretion disk model is shown in Figure 3.

5. Discussion and Conclusions

Overall, the best fit to the *FUSE* spectrum of MV Lyr in its high state consists of a composite WD + disk + BL model with a mass accretion rate $\dot{M} = 2 \times 10^{-9} M_{\odot}/\text{yr}$. There are two equally acceptable BL solutions, either a broad extended (two-ring) BL with a rather low temperature (in the range $100,000\text{K}$ - $150,000\text{K}$), or a thin (one-ring) BL with a higher temperature ($175,000\text{K}$). The WD temperature is probably higher than the $44,000\text{K}$ found in the low state, due to ongoing accretion but it affects only slightly the quality of the fitting

of the models, we discuss this further at the end of this section.

Since the modeling of the *FUSE* spectrum generates more than one solution over a finite spectral range, one must consider the bolometric luminosity of each component for comparison with equations (2) & (6). For each model, the total luminosity of the BL is computed assuming it radiates as a black body. This is a reasonable assumption, as in this regime the BL is most probably optically thick (Godon et al. 1995; Popham & Narayan 1995). The two components of temperature T_1 & T_2 (given in Table 2), and with radii $r_1 = 1.05R_*$ and $r_2 = 1.2R_*$ are added. One then simply uses the Stefan-Boltzmann law and area of each ring to find the total BL luminosity. The bolometric luminosity obtained is then compared with the theoretical expectation in eq.(6) using eq.(2). For almost all the disk+BL models listed in Table 2 it is found that the computed bolometric BL luminosity is larger than the disk luminosity. The discrepancy is even larger for the model with $\dot{M} = 1 \times 10^{-9} M_\odot/\text{yr}$. The only models for which the BL bolometric luminosity is smaller than the disk luminosity (eq.6) is for an extended BL (two-ring model) with a temperature as low as 100,000K. For that model the bolometric BL luminosity is 93% of the disk luminosity, implying a rotational velocity (eq.6) of less than 4% its Keplerian value or about 135km/s.

With an inclination $i = 10^\circ \pm 3^\circ$ and a projected rotational velocity of $200 \pm 50\text{km/s}$ (as derived in the low state), the (non-projected) rotational velocity should be in the range $667\text{km/s} < V_{rot} < 2050\text{km/s}$, or $0.18 < \Omega_*/\Omega_K < 0.54$ (the lower limit is for a velocity of 150km/s and $i = 13^\circ$, while the upper limit is for 250km/s and $i = 7^\circ$). This produces a BL luminosity in the range $0.68 > L_{BL}/L_{disk} > 0.21$. For the BL model to agree with the upper limit, one could reduce the BL temperature (by 10,000K) or increase the mass accretion rate (by 1/3, such a model is listed at the end of Table 2) or both. However, one notes that the error in the WD mass of $0.1M_\odot$ (~ 0.2 in $\log g$) produces a computed L_{BL}/L_{disk} between 0.55 (for a $0.9M_\odot$ WD mass) and ~ 1.5 (for a $0.7M_\odot$ WD mass). Since the BL model used here is rather simplistic, a perfect agreement between the computed bolometric luminosity of the BL and that computed from eq.6 is not expected. However, within the limits of the errors, the results of the BL model are consistent with a broad BL (of size $\sim 0.2R_*$) with a rather low temperature ($\sim 100,000\text{K}$ or slightly less) and a mass accretion rate of the order of $\approx 2 \times 10^{-9} M_\odot/\text{yr}$ (or slightly larger). These models are located the lower part of Table 2 and the fit improves (lower χ_ν^2 and better distance) as the temperature of the WD increases, reaching a best fit for $T = 70,000\text{K}$. Though the temperature of the WD is certainly not that high, this certainly points to the fact that the temperature of the WD is elevated during the high state reaching $\sim 50,000\text{K}$ or a little higher.

6. acknowledgements

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Table 1. System Parameters for MV Lyr

Parameter	Value	Reference
M_{wd}	$0.73\text{-}0.8M_{\odot}$	this work; Hoard et al. (2004)
R_{wd}	7,440km	based on models of Wood (1995)
M_{2nd}	$0.3M_{\odot}$	Hoard et al. (2004)
i	$10^{\circ} \pm 3^{\circ}$	Schneider et al. (1981); Skillman et al. (1995) Linnell et al. (2005)
E(B-V)	0	Bruch & Engel (1994)
P	3.19hr	Skillman et al. (1995)
d	$\sim 500 - 550\text{pc}$	this work; Hoard et al. (2004)
\dot{M}	$2 \times 10^{-9}M_{\odot}/\text{yr}$	This work; Linnell et al. (2005)

Table 2. Accretion Disk & Boundary Layer Synthetic Spectral Model Fits

Model	$\dot{M} \times 10^9$ (M_\odot/yr)	T_{wd} (10^3K)	d (pc)	T_1 (10^3K)	T_2 (10^3k)	WD/disk %	χ_ν^2	Figure
disk	1.0	44	301	25.9	32.2	19/81	3.066	1
disk	2.0	44	428	30.7	38.3	10/90	1.923	
disk	3.5	44	557	35.4	44.1	6/94	1.379	
disk	5.0	44	666	38.7	48.2	4/96	1.270	
...
disk+BL d	1.0	44	370	175	32.2	13/87	0.856	
disk+BL 1	1.0	44	349	150	32.2	14/86	1.083	
disk+BL 2	1.0	44	336	125	32.2	16/84	1.376	
disk+BL 3	1.0	44	327	100	32.2	16/84	1.376	
disk+BL 4	1.0	44	448	150	150	9/91	1.302	
...	
disk+BL d	2.0	44	480	175	38.3	8/92	1.019	
disk+BL 1	2.0	44	464	150	38.3	8/92	1.203	
disk+BL 2	2.0	44	454	125	38.3	9/91	1.358	2
disk+BL 3	2.0	44	447	100	38.3	9/91	1.485	
disk+BL 4	2.0	44	538	150	150	6/94	1.058	
disk+BL 5	2.0	44	507	125	125	7/93	0.993	
disk+BL 6	2.0	44	484	100	100	8/92	1.056	
disk+BL da	2.0	44	516	175	100	7/93	0.985	
disk+BL 7	2.0	44	500	150	100	7/93	1.000	
disk+BL 8	2.0	44	491	125	100	7/93	1.025	
...
disk+BL da	2.0	44	516	175	100	7/93	0.985	2
disk+BL da	2.0	50	521	175	100	8/92	0.995	
disk+BL 4	2.0	44	538	150	150	6/94	1.058	
disk+BL 4	2.0	50	542	150	150	8/92	1.078	
disk+BL 4	2.0	60	548	150	150	10/90	1.082	
disk+BL 4	2.0	70	555	150	150	12/88	1.090	
disk+BL 6	2.0	44	484	100	100	8/92	1.056	
disk+BL 6	2.0	50	489	100	100	9/91	1.030	

Table 2—Continued

Model	$\dot{M} \times 10^9$ (M_\odot/yr)	T_{wd} (10^3K)	d (pc)	T_1 (10^3K)	T_2 (10^3k)	WD/disk %	χ^2_ν	Figure
disk+BL 6	2.0	60	496	100	100	12/88	1.012	
disk+BL 6	2.0	70	503	100	100	14/86	0.989	
disk+BL 6	2.7	50	545	100	100	8/92	1.068	

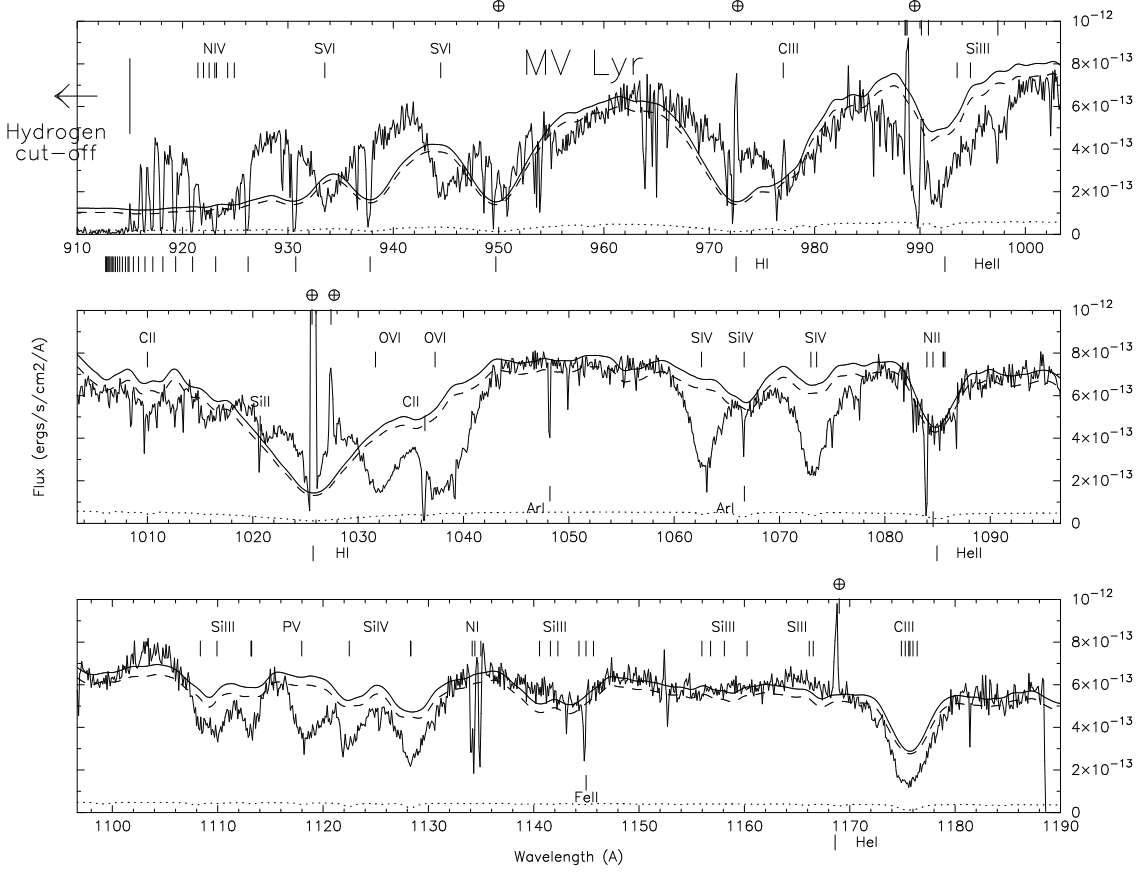


Fig. 1.— The *FUSE* spectrum of MV Lyr in its high state is modeled with a 44,000K WD (dotted line), with a mass $0.8M_{\odot}$ and a standard accretion disk (dashed line) with $\dot{M} = 3.5 \times 10^{-9}M_{\odot}/\text{yr}$ and $i = 10^{\circ}$. The combined model WD + disk is the solid black line. This gives a matching distance of 557pc. The model cannot match the flux level in the short wavelength range ($< 950\text{\AA}$). In order to fit that region the mass accretion rate has to be increased, and this increases the distance to twice the distance of MV Lyr.

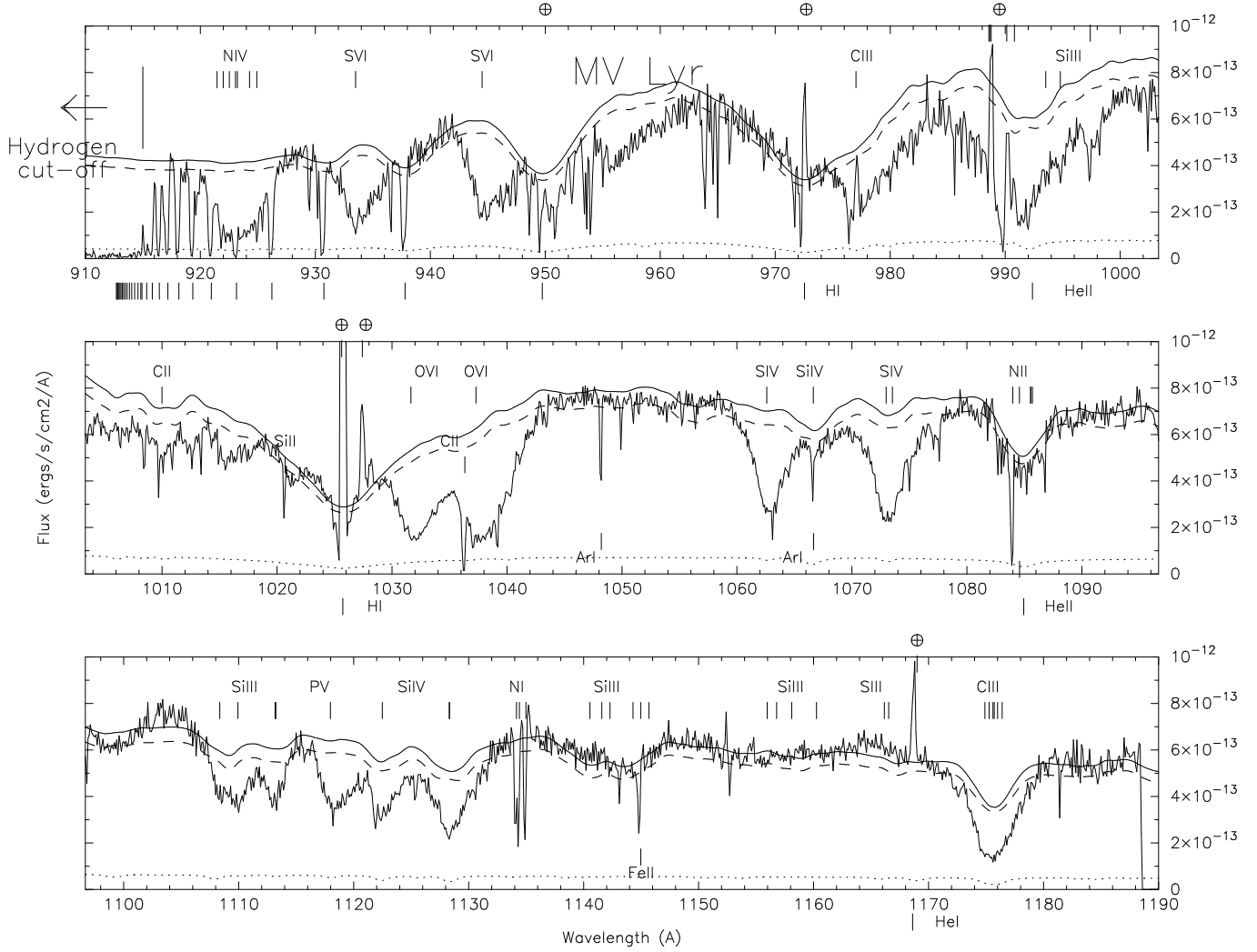


Fig. 2.— The *FUSE* spectrum of MV Lyr in its high state is modeled with a composite WD + disk model which includes the BL. The WD model (dotted line) has a temperature of 44,000K and a mass $0.8M_{\odot}$, the accretion disk model (dashed line) has a mass accretion rate of $\dot{M} = 2.0 \times 10^{-9} M_{\odot}/\text{yr}$ and $i = 10^{\circ}$. The BL is modeled as the two inner rings of the disk with a temperature of 150,000K. The combined model WD + disk is the solid black line. This gives a distance of 538pc. The WD contributes only 6% of the flux in the *FUSE* spectral range.

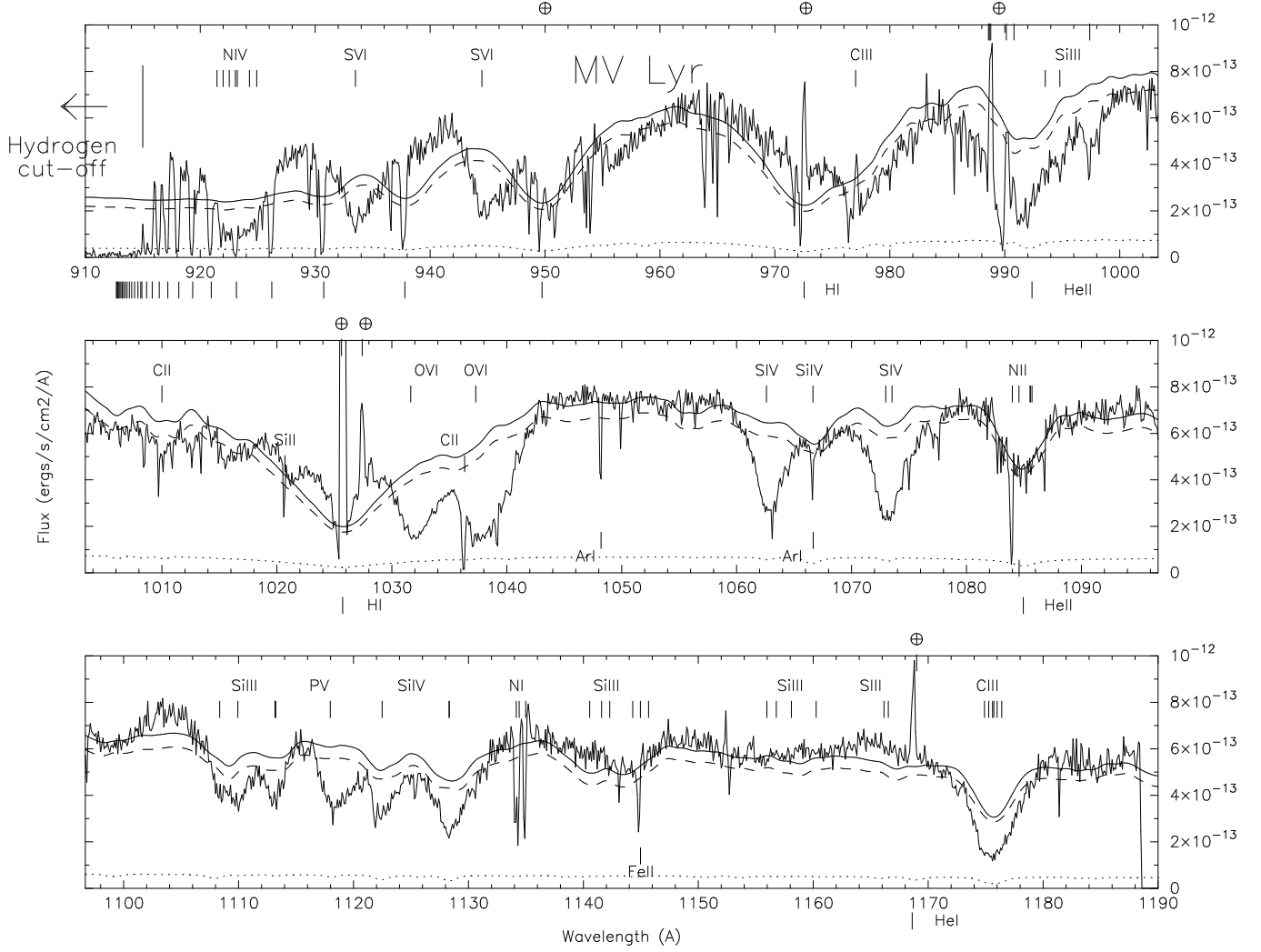


Fig. 3.— The *FUSE* spectrum of MV Lyr in its high state is modeled with a composite WD + disk model which includes the BL . The WD model (dotted line) has a temperature of 50,000K and a mass $0.8M_{\odot}$, the accretion disk model (dashed line) has a mass accretion rate of $\dot{M} = 2.0 \times 10^{-9} M_{\odot}/\text{yr}$ and $i = 10^{\circ}$. The BL is modeled as the two inner rings of the disk with a temperature of 100,000K. The combined model WD + disk is the solid black line. This gives a distance of 489pc. The WD contributes 9% of the flux in the *FUSE* spectral range.